Pion, muon decays and weak interaction symmetries

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Abstract

We review the recent measurements of the rare pion decays: $\pi^+ \to \pi^0 e^+\nu$ (beta, π_{e3}, or π_β decay), radiative decay $\pi^+ \to e^+\nu\gamma$ ($\pi_{e2\gamma}$ or RPD), and $\pi^+ \to e^+\nu$ (π_{e2}), as well as the radiative muon decay, $\mu \to e\nu\bar{\nu}\gamma$, their theoretical implications, and prospects for further improvement.

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Thanks to exceptionally well controlled theoretical uncertainties, decays of light mesons, particularly of the pion, are understood at very high precision, typically a few parts per 10^4, or better (see, e.g., Refs. [1, 2, 3]. Hence, pion decays present fertile ground for testing predictions of the standard model (SM), as well as for setting constraints on processes and particles outside the SM. Muon decays are theoretically cleaner yet, and provide direct information concerning the symmetry properties of the weak interaction itself, e.g., departures from its $V-A$ form.

The PIBETA experiment, with measurements in 1999–2001 and 2004 at the Paul Scherrer Institute (PSI), Switzerland, was primarily designed to improve the accuracy of the π_β decay branching ratio. Pion decays at rest were detected in an detector system [4, 5] shown schematically in Fig. 1. Normalizing to the number of observed $\pi^+ \to e^+\nu$ (π_{e2}) decays, we determined the branching ratio value $B^{\rm ex-n}(\pi^+ \to \pi^0 e^+\nu) = 1.036(4)_{\rm stat}(4)_{\rm syst}(3)_{\rm e2}\times 10^{-8}$, where the first uncertainty is statistical, the second systematic, and the third arises from $\Delta B(\pi_{\rm e2})$, experimental π_{e2} branching ratio uncertainty[6] . Normalizing instead to the more precise theoretical value of $B(\pi_{\rm e2})$ [3] yields

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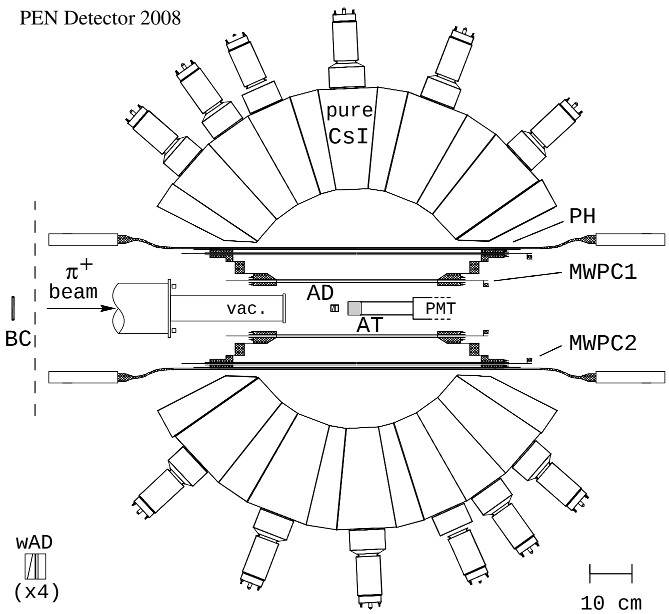

Figure 1: Schematic cross section of the PIBETA/PEN apparatus, shown here in the 2008 PEN run configuration, with its main components: beam entry with the upstream beam counter (BC), wedged active degrader (wAD) and target (AT), cylindrical multiwire proportional chambers (MWPC's), plastic hodoscope (PH) detectors and photomultiplier tubes (PMT's), 240-element pure CsI electromagnetic shower calorimeter and its PMT's. BC, wAD, and PH detectors are made of plastic scintillator.

$B^{\text{th-n}}(\pi^+ \to \pi^0 e^+\nu) = 1.040(4)_{\text{stat}}(4)_{\text{syst}} \times 10^{-8}$. Both results agree well with the SM prediction, and represent the best test to date of vector current conservation (CVC) in a meson.

Concurrently with the π_{e3} decay, the PIBETA collaboration has measured the $\pi^+ \to \mathrm{e}^+\nu\gamma$ (RPD) branching ratio over a wide region of phase space. Two sets of amplitudes contribute to RPD: the inner-bremsstrahlung, IB, fully described by QED, and the structure-dependent amplitude, SD. The standard V−A electroweak theory requires only two pion form factors, F_A, axial vector, and F_V, vector, to describe the SD amplitude. The vector form factor is strongly constrained by the CVC hypothesis to $F_V = 0.0259(9)$.

Minimum-χ^2 fits to the measured (E_{e^+}, E_γ) energy distributions result in the weak form factor value of $F_A = 0.0119(1)$ with a fixed value of $F_V = 0.0259$. An unconstrained fit yields $F_V = 0.0258(17)$ and $F_A = 0.0117(17)$ in a tightly correlated narrow band (see Fig. 2). In addition, we have measured $a = 0.10(6)$ for the dependence of F_V on q^2, the $\mathrm{e}^+\nu$ pair invariant mass squared, parametrized as $F_V(q^2) = F_V(0)(1 + a \cdot q^2)$. The branching ratio for the kinematic region $E_\gamma > 10\,\text{MeV}$ and $\theta_{\mathrm{e}^+\gamma} > 40^\circ$ is measured to be $B^{\text{exp}} = 73.86(54) \times 10^{-8}$. Earlier deviations we found in the high-E_γ/low-E_{e^+} kinematic region [7] are resolved, and we find full compatibility with CVC and standard $V{-}A$ calculations without a tensor term—we find $-5.2 \times 10^{-4} <$

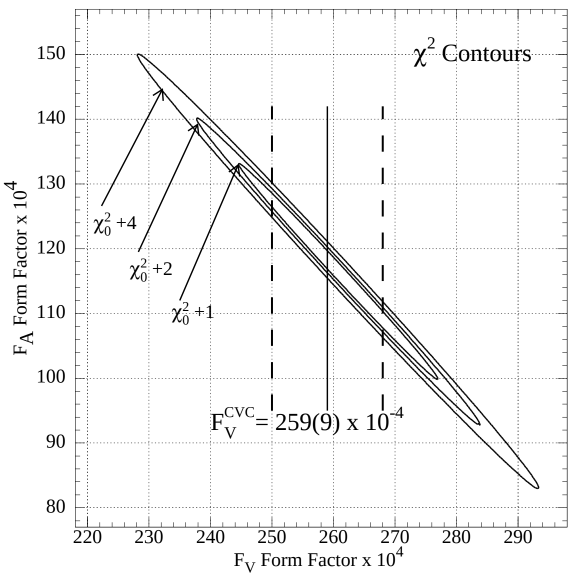

Figure 2: Contour plot of loci of constant χ^2 for the minimum value χ_0^2 plus 1, 2, and 4 units, respectively, in the F_A-F_V parameter plane, keeping the parameter $a = 0.041$. The range of the CVC prediction, $F_V = 0.0259(9)$ is indicated.

$F_T < 4.0 \times 10^{-4}$ with 90% condidence. We also derive new values for the pion polarizability at leading order, $\alpha_E = 2.78(10) \times 10^{-4}\,\mathrm{fm}^3$, and neutral pion lifetime, $\tau_{\pi 0} = (8.5 \pm 1.1) \times 10^{-17}\,\mathrm{s}$.

Radiative muon decay (RMD) offers a particularly sensitive means for testing the $V\!-\!A$ nature of the weak interaction through $\bar{\eta}$, the only Michel parameter not accessible in ordinary μ decay. RMD events with energetic photons are required to evaluate $\bar{\eta}$. Along with other Michel parameters, $\bar{\eta}$ sets limits on departures from the $V\!-\!A$ weak interaction form ($\bar{\eta}_{SM} \equiv 0$).

With more than 4×10^5 RMD events, the 2004 PIBETA data set leads to a preliminary result: $B(E_\gamma > 10\,\mathrm{MeV},\, \theta_{e\gamma} > 30^\circ) = 4.40(2)_{\mathrm{stat}}(9)_{\mathrm{syst}} \times 10^{-3}$, 14 times more precise than the previous world average[9]; here the systematic uncertainty will be reduced by improving low-energy photon scattering simulation. The best fit for B is obtained for $\bar{\eta} = -0.084 \pm 0.050(\mathrm{stat.}) \pm 0.034(\mathrm{syst.})$, yielding upper limits on the allowed value of $\bar{\eta} \leq 0.033$ and $\bar{\eta} \leq 0.060$, with 68% and 90% confidence, respectively. Combined with previous measurements of $\bar{\eta}$, this reduces the known upper limit by a factor of 2.5 to $\bar{\eta}_{\text{WORLD AVG}} \leq 0.028$, with 68% confidence [10].

Historically, the $\pi \to e\nu$ (or π_{e2}) decay, provided an early strong confirmation of the $V\!-\!A$ nature of the electroweak interaction. At present, its branching ratio is understood at the level of better than one part in 10^4 [3]. Experimental precision, however, lags behind by over an order of magnitude.

Because of the large helicity suppression of the π_{e2} decay, its branching ratio is highly susceptible to even slight non-$V-A$ contributions from new physics, making this decay a particularly suitable subject of study.

The PEN experiment [11] uses a modified PIBETA detector system to carry out a measurement of $B(\pi_{e2})$ to an accuracy of $\Delta B/B \leq 5 \times 10^{-4}$, at PSI. During engineering runs in 2007 in 2008 the collaboration developed the required intense low energy pion beam tunes and upgraded key detector components, including a mini time projection chamber to map the beam. To date, the experiment has observed over 7×10^{10} tagged pion stops in the target, and recorded over 4×10^6 π_{e2} decays before cuts. PEN will run in 2009-10 in order to complete the required event statistics and key systematic studies.

In conclusion, the PIBETA experiment has improved, by an order of magnitude or better, the accuracy of rare decays: the pion beta (π_{e3}), radiative pion ($\pi_{e2\gamma}$), and radiative muon decays. In doing so, PIBETA has verified CVC and SM predictions at new levels in a meson, and improved the precision of pion structure parameters (F_V, F_A, F_T form factors, polarizability, closely related to low-energy effective QCD lagrangian parameters $L_9^r + L_{10}^r$). Through the $B(\mu \to e\nu\bar{\nu}\gamma)$ and $\bar{\eta}$ measurement we have made possible new tests of the $V-A$ nature of the weak interaction. PEN, the successor experiment, is well on its way to improving the precision of the π_{e2} branching ratio, with the prospect of setting new limits on light lepton universality, and on a variety of non-SM processes manifested primarily through pseudoscalar contributions. The PEN data set will more than double our 2004 PIBETA run statistics for RPD and RMD events, leading to further improvements in precision, while the π_β event statistics will increase only slightly.

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